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Material Properties

Effect of carbon black on the mechanical performances of magnetorheological elastomers

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Abstract

Several magnetorheological elastomer (MRE) samples, with different weight percentages of carbon black, were fabricated under a constant magnetic field. Their microstructures were observed by using an environmental scanning electron microscope (SEM), and their mechanical performance including magnetorheological (MR) effect, damping ratio and tensile strength were measured with a dynamic mechanical analyzer (DMA) system and an electronic tensile machine. The experimental results demonstrate that carbon black plays a significant role in improving the mechanical performance of MR elastomers. Besides the merits of high MR effect and good tensile strength, the damping ratio of such materials is much reduced. This is expected to solve a big problem in the application of MR elastomers in practical devices, such as in adaptive tuned vibration absorbers.

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Keywords: Magnetorheological elastomers; Carbon black; Microstructures; Mechanical performances

1. Introduction

Magnetorheological elastomers (MREs) are a class of smart material whose mechanical properties (such as the modulus and damping ratio) can be reversibly and rapidly controlled by an external magnetic field [1–5]. This is achieved via the addition of microsized magnetizable particles into the elastomers or rubber-like materials. When such a mixture is exposed to a magnetic field before curing, the field-induced interactions between particles can result in the formation of an anisotropic ordered preconfiguration such as chains or more complex three-dimensional structures. After the mixture is cured or cross-linked, these structures are locked into place. When such prepared MREs are exposed to an applied magnetic field, the field-induced dipole magnetic forces between the particles result in the field dependence of mechanical performance. The change of the modulus is usually termed an MR effect.

Because of their unique characteristics, MREs have attracted increasing attention and have obtained broad application prospects recently. Based on MREs, Elie et al. [6] designed an apparatus to measure displacement and force, Ginder et al. [7], Lerner and Cunefare [8] and Deng et al. [9]

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developed adaptive tuned vibration absorbers, Ottaviani et al. [10] provided a releasable attachment and Watson [11] exploited a variable stiffness suspension bushing. Among these applications, the development of MREs-based adaptive tuned vibration absorbers is expected to offer promising applications in industry. By choosing its natural frequency close to the excitation frequency, the MRE-based absorber can reduce vibration in widely varying excitation frequency systems, in contrast to the effectiveness of only narrow frequency ranges for traditional vibration absorbers. It is noted that the stiffness varying change is dominated by MR effects. Generally, the higher the MR effect, the wider the natural frequency range. Thus, to develop high-efficiency MRE-based shock absorbers, the primary objective is focused on the development of MRE materials with high MR effect. Increasing the magnetic particle content [12,13] and using soft materials as the matrix [1,14] have been used to fabricate MREs with high MR effects. For example, the increase in the magnetic particle content leads to a sharp rise in the damping ratio and decline of tensile strength [15]. However, it is found that the absorbing effect is extremely influenced by the damping ratio: low damping ratio leads to high vibration reduction effect while high damping ratio results in poor vibration suppression [16]. In addition, the soft matrix has generally a low level of tensile strength.

Therefore, to develop new MREs with high MR effect, good tensile strength and relatively low damping ratio are the major motivations of the project. To this end, carbon black is selected as an addition to modify and improve MRE mechanical properties, because carbon black is a important reinforcing filler in polymer engineering, especially in rubber technology [17].

This paper is organized as follows. Firstly, the fabrication of various MRE samples with different carbon black additions is introduced. The microstructure observation of MRE samples and mechanical property characterization is then described. Finally, the effect of carbon black on mechanical performances of MREs is summarized.

2. Experimental

2.1. Preparation of MRE materials

The fabrication of MREs consists of three major steps: mixing, pre-forming configuration and curing.

Table 1
The composition of each sample prepared

Sample	Composition (V%)		
	Magnetic particles (%)	Carbon black (%)	Matrix (48.5% natural rubber, 50% plasticizers and 1.5% other additives) (%)
1	33	0	67
2	33	4	63
3	33	7	60
4	0	6	94

During fabrication, each composition was firstly mixed homogeneously, then the magnetic particles formed the ordered structure and, finally, the sample became an elastomer. The mechanical–magnetic coupling fabrication system is detailed in Ref. [15]. By this method, three MRE samples with different compositions, as shown in Table 1, were prepared under an external magnetic flux density of 1000 mT. As shown in this table, the magnetic particle content for three samples, 1–3, was fixed at 33%, but the carbon black content for these samples was increased from 0 to 7%. For comparison, sample 4 was prepared with pure carbon black and without any magnetic particles.

The magnetic particles used were provided by BASF (German, type SU) with an average diameter of 1.7 μm. The carbon black (type N330, with a range of diameter 26–30 nm), natural rubber, plasticizer and other additives were provided by Hefei Wangyou Rubber Company of China.

2.2. Observation of microstructure

The microstructures of four MRE samples were observed using an environmental scanning electron microscope (SEM, Philips of Holland, model XT30 ESEM-MP). These samples were firstly cut into pieces with surface area of 3 mm × 3 mm, each surface of which was coated with a thin layer of gold and then placed into the SEM. The microstructure of the samples was observed at an accelerating voltage of 15 kV. Through the microstructural observation, the interactions between rubber and magnetic particles were obtained.

2.3. Measurement of MREs' viscoelastic property

Viscoelastic properties of these samples were measured using a modified dynamic mechanical

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analyzer (DMA) (Triton Technology Ltd., UK, model Tritec 2000B). In this system, a self-made electromagnet was introduced to generate a variable magnetic flux density up to 1 T. Both strain amplitude sweep and frequency sweep modes were conducted to test viscoelastic properties, such as shear modulus and loss factor, of MRE samples under various magnetic fields.

In the experiments, the samples were cut into cuboids of 10 mm × 10 mm × 3 mm. The range of the external magnetic field was 0–800 mT, the driving frequency was fixed at 1 Hz and the dynamic strain amplitude was set as 0.3%. The experiments were carried out at room temperature.

2.4. Testing of tensile strength

The tensile strength is one of the most important physical properties of rubber-based materials. In this study, the tensile strength of the MRE samples was tested by an electronic tensile machine (Jiangdu Jingcheng Test Instruments Factory, China, model JPL-2500). Dumbbell test pieces cut from the samples were used with a grip separation rate of 100 mm per minute.

3. Results and discussion

3.1. MR effect

The shear modulus of the MRE samples with different compositions was measured under various magnetic fields from 0 to 800 mT, as shown in Fig. 1. As can be seen from this figure, the shear modulus of samples 1–3 shows an increasing trend with magnetic field before they reach magnetic saturation at high field strength. These results agree well with theoretical analysis using field-induced dipole magnetic forces between the particles [18,19]. In contrast, the shear modulus of sample 4 does not change at all with the external magnetic field. This is obvious as there are no particles to induce MR effect. This result also indicated that carbon black did modify particle properties and, consequently, influenced the MR effect. This effect is clearly shown in Table 2, where all these data were collected from the experimental results shown in Fig. 1. In this table, G_0 denotes the MRE samples' zero-field modulus, ΔG_{max} denotes the saturated field-induced modulus, and $\Delta G_{max}/G_0$ denotes the relative MR effect. It can be seen from this table that G_0 is enhanced with the increase in carbon

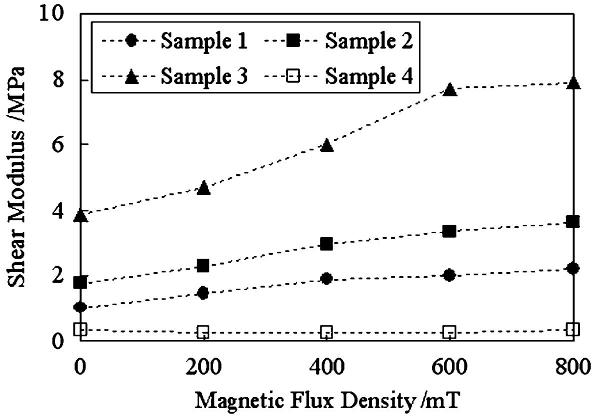

Fig. 1. The shear modulus of the samples with different compositions and different magnetic flux density.

Table 2
The MR effect of each sample

Sample	Property		
	G_0 (MPa)	ΔG_{max} (MPa)	$\Delta G_{max}/G_0$ (%)
1	1.05	0.92	88
2	1.76	1.67	95
3	3.87	4.03	104
4	0.24	<0.01	<5

black content. The Guth–Gold equation [20] claims that the effective shear modulus of the composite increases steadily with the volume ratio of the filler added. So, the higher volume fraction of carbon black leads to a higher shear modulus, as indicated in this table.

From Table 2, it is also interesting to see that ΔG_{max} has great dependence on the carbon black content. However, the result of sample 4 shows there is no additional modulus caused by the carbon black directly. The reason for the difference in ΔG_{max} may be found in Fig. 2, which shows the microstructures observed by the SEM. In Fig. 2(d), the sample including only carbon black without magnetic particles shows a very homogeneous structure. This indicates that there is good bonding between the fine carbon black powder and the rubber. However, in Fig. 2(a), the sample including only magnetic particles without carbon black shows a poor bond between the magnetic particles and the rubber, with many voids existing between the two phases. When some carbon black is added, the bond

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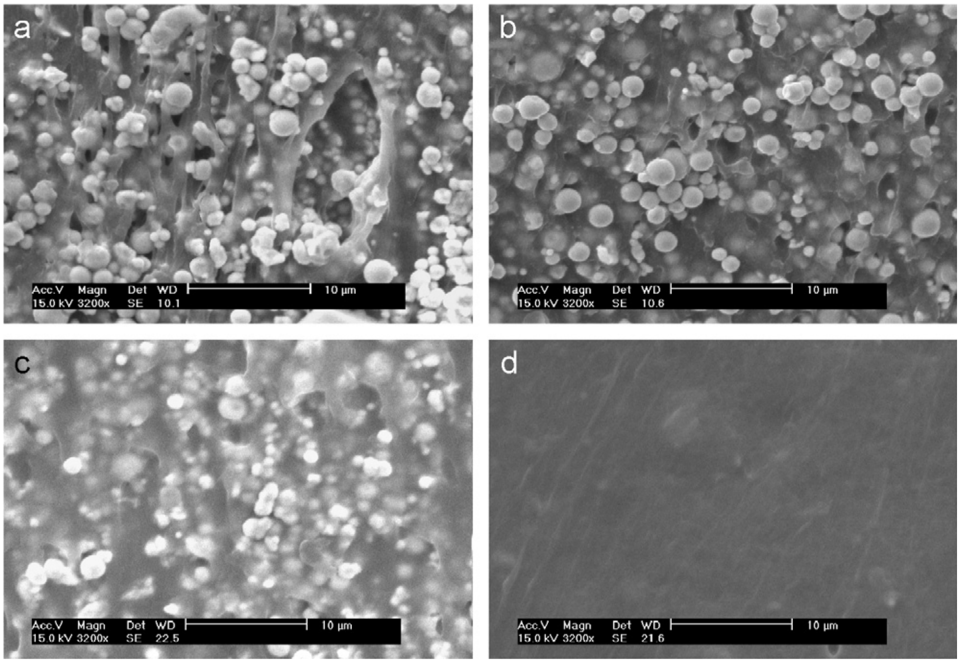

Fig. 2. The microstructure of the samples observed by an environmental scan electronic microscope. Images (a)–(d) correspond to samples 1–4, respectively.

is improved, as shown in Fig. 2(b). When more carbon black is added, the magnetic particles are embedded in and well bound with the rubber matrix. Although the mechanism of the interaction between the magnetic particles and the carbon black is still not very clear, the microstructure of MRE is indeed affected by the addition of the carbon black. If there are several MRE samples all with the same volume, and some are well bound and some are poorly bound, then it is reasonable to assume that the well-bound ones have a higher magnetic particle volume than the poorly bound ones. This is because inner voids occupy the place of magnetic particles and lead to a decrease in the volume of magnetic particles. Many groups have proved that the magnetic particle content plays a very important role in the MR effect [12,13,15]. Therefore, the MRE sample including carbon black has a well-bound structure and, consequently, induces a high MR effect. Accordingly, the relative MR effect ($\Delta G_{max}/G_0$) is enhanced with the increase in the carbon black content. In addition, the zero-field modulus also grows sharply with the increase in carbon black, as shown in Table 2. So, in order to get a high relative MR effect, the carbon black content should not be too high.

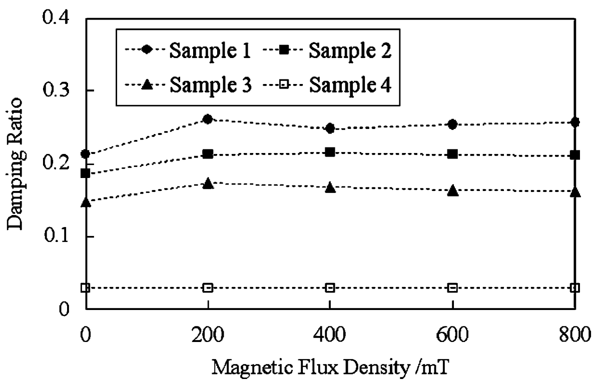

Fig. 3. The damping ratio of the samples with different compositions and different magnetic flux density.

3.2. Damping ratio

The damping ratios of these four MRE samples under various magnetic fields were experimentally characterized with the modified DMA. The results are shown in Fig. 3. As seen from this figure, the results in sample 4 also prove that there is no interaction between the carbon black particles in the magnetic field. With increasing magnetic field, the damping ratios of the other samples show an

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increasing trend until a maximum value is obtained, then a decreasing trend later, which has not been reported previously. It is known that the damping ratio of composite materials reflects the ability of the materials to dissipate energy, which mainly comes from the interaction among different inner phases [21]. The energy loss at the interface is a key factor in the interaction, and depends on the value of the interaction force multiplied by the slipping displacement. When a low magnetic field is applied to the MRE sample, a force between magnetic particles occurs and transfers to the matrix. Then, the interaction force between the particles and the matrix is enhanced. In this condition, more energy is dissipated on the interface slipping. Hence, the MRE sample's damping ratio is macroscopically increased by the magnetic field. It is also noted that the slipping displacement is influenced by the interaction force. When a high magnetic field is applied to the MRE sample, the strong interaction force between the particles and the matrix decreases the slipping displacement. Then, the energy dissipation is reduced and the damping ratio is decreased when the magnetic field further increases.

Fig. 3 also shows the effect of carbon black content on the damping ratio. As the content of carbon black increases, the damping ratio is decreased. According to the above slipping method, a large slipping displacement occurs in the poorly bound sample and results in a high damping ratio. On the contrary, the well-bound sample shows a low damping ratio. These conclusions were also justified by the microstructures of each sample, as shown in Fig. 2.

The above results indicate that the addition of the carbon black can reduce the MRE sample's damping ratio. This conclusion is significant for some devices based on MREs—for example, the adaptive tuned vibration absorbers using MRE as variable stiffness springs [7–9]. It is found that the absorber's effect is extremely influenced by the damping, low damping leads to high vibration reduction while high damping results in poor vibration suppression [16]. In order to get a high MR effect, large numbers of magnetic particles are often added into the matrix. However, this method increases the damping ratio sharply [15]. In such a case, adding carbon black into the matrix would provide an effective way to develop the desired MR elastomers with high MR effect and low damping ratio.

Table 3
The tensile strength of each MRE sample

Sample	Tensile strength/MPa
1	2.37
2	3.25
3	3.52

3.3. Tensile strength

The tensile strengths of MRE samples with different carbon black contents are listed in Table 3. The result indicates that the carbon black is also able to enhance the tensile strength of MRE. As shown in this table, when the carbon black content increases from 0 to 7%, the tensile strength of the samples increases from 2.37 to 3.52 MPa, a remarkably relative increase of 48.5%. This effect may be explained in two aspects. Firstly, carbon black plays a role in traditional rubber materials. It evens out the inner stresses in rubber and lets more molecular chains effectively carry the load. The homogeneous stress distribution causes a high improvement in tensile strength. Secondly, from Fig. 2 it is seen that the carbon black has an effect not only on the rubber but also on the bound condition between the rubber and magnetic particles. The inner voids lead to stress concentration within the sample, which results in rupture at a low stress. Therefore, the MREs' tensile strength is remarkably reinforced by the addition of carbon black.

4. Conclusions

Several magnetorheological elastomer (MRE) samples with different carbon black content were prepared. The microstructures of these samples were observed and their mechanical performances were characterized. The effects of the carbon black on the mechanical performances, including MR effect, damping ratio and tensile strength, were experimentally investigated. The addition of the carbon black into the matrix leads to a well-bound microstructure and results in high MR effect, low damping ratio and improved tensile strength. These results can hopefully be applied to solve the shortcomings existing in conventional MREs. The application of such materials in adaptive tuned vibration absorbers is also discussed.

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